2023 Theory and Simulation of Disruptions Workshop, July 19-21

Simulation study of the influence of grad-*B* drift on pellet ablation dynamics

Roman Samulyak

Stony Brook University

Stony Brook, NY

roman.samulyak@stonybrook.edu

Influence of grad-*B* drift on pellet ablation dynamics

- Grad-B drift establishes the shielding length of the ablation cloud

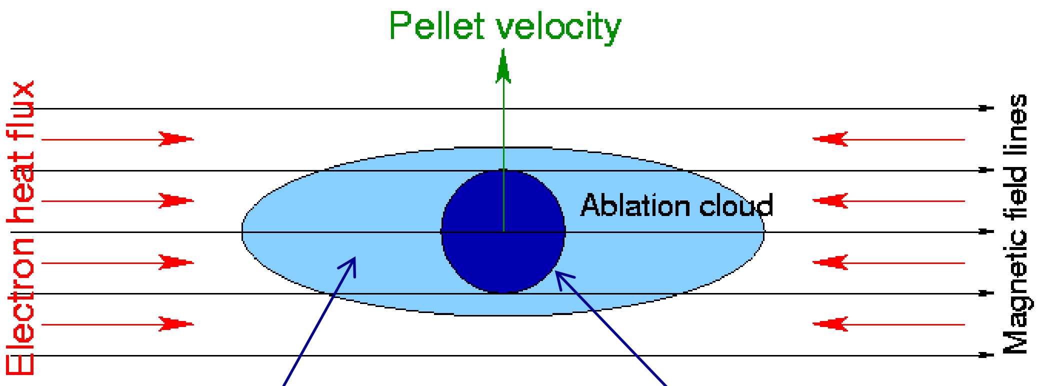
- Strongly influences the pellet ablation rate in magnetic fields

- Affects the deposition of ablated material in tokamaks. Improves the efficiency of HFS injection compared to the LFS injection

- Grad-B drift creates asymmetry and non-uniform heating of the ablation cloud that leads to the pellet rocket effect. The rocket effect may strongly influence trajectories and the penetration of pellets and SPI fragments in tokamaks *(main topic for today's talk)*

- Grad-B drift is among the main factors causing striation instabilities of ablation clouds. Striation instabilities manifest themselves in periodic separation of pellets from the ablation clouds after which pellets become exposed to unattenuated heat fluxes. Striations result in non-uniform in time ablation and material deposition *(future talk)*

Lagrangian particle code for ablation of pellets / SPI fragments



- Phase transition (ablation model) for pellet surface

- Low magnetic Re MHD equations
- Kinetic model for the electron heating by hot electrons
- Models for ablation by runaway electrons
- EOS with atomic processes
- Radiation models
- Grad B drift models
- Pellet cloud charging models

- Highly adaptive, massively parallel 3D particle code
- Lagrangian treatment of ablation material eliminated numerous numerical difficulties associated with multiscale issues of the pellet ablation
- Supports large number of SPI fragments in 3D

- LP algorithm: R. Samulyak, X. Wang, H.-S. Chen, J. Comput. Phys. (2018), 362 1-19.
- Massively-parallel LP: S. Yuan, R. Samulyak et al, MRC (2023) 129 104075.

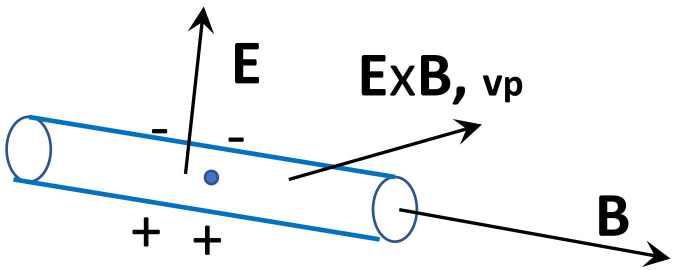
- LP application to pellets / SPI: R Samulyak, S Yuan, N Naitlho, PB Parks, Nuclear Fusion 61 (4), 046007 (2021).

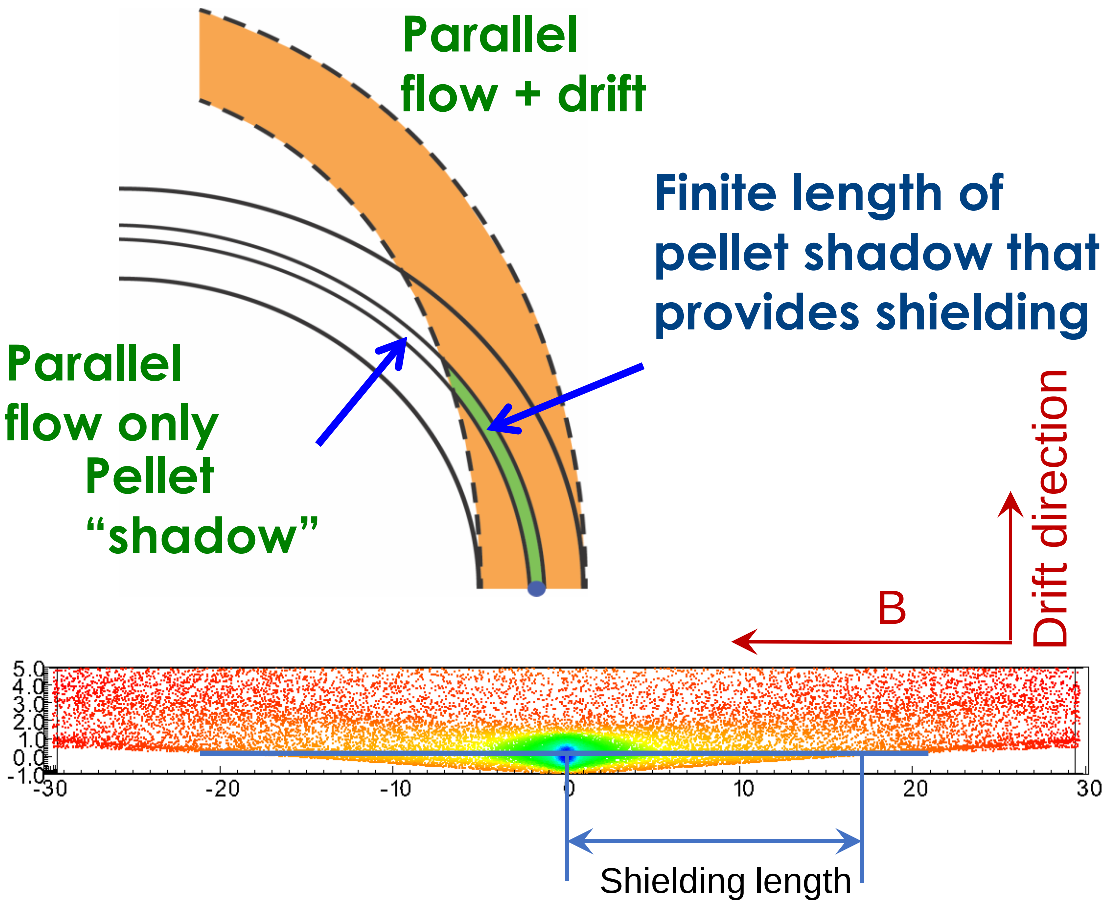
- Validation using neon experimental data at DIII-D: E. M. Hollmann, N. Naitlho, S. Yuan, R. Samulyak, P. Parks, D. Shiraki, J. Herndal, and C. Marini, Phys. Plasmas 29, 092508 (2022); doi: 10.1063/5.0106724.

- Application to SPI ablated by high-energy RE beam in ITER: S. Yuan, N. Naitlho, R. Samulyak, E. Nardon, B. Pegoruie, P. Parks, M. Lehnen, Phys. Plasmas 29, (2022), 103903

The LP code is a significant improvement over our 2D front-tracking-based pellet code [NF2007, PoP2009, PoP2021]

Transverse flow dynamics in 3D Lagrangian particle pellet code





Polarization ExB drift

- Weakly ionized pellet ablation cloud becomes polarized while traveling across the magnetic field
- ExB force is responsible for the drift of the cloud with the same velocity as the pellet velocity
- In a uniform B field, the flow would extend along the magnetic field line passing through the pellet center, eventually completely shielding the pellet and stopping the ablation
- In older 2D simulations, we assumed that the finite shielding length is an input parameter (estimated as 16 cm)

Grad-B drift

- LP code computes the shielding length self-consistently

- Grad-B drift model. We assume that the electrostatic potential is uniform along each magnetic field line. The equation for the grad-B drift velocity in the large-R direction is

$$\frac{\mathrm{d}v_{\mathrm{D}}}{\mathrm{d}t} = \frac{2\langle P(1+\frac{M_{\parallel}^{2}}{2}) - P_{\infty}\rangle}{R\langle\rho\rangle} - u_{\mathrm{D}}\frac{2B_{\parallel}^{2}}{\mu_0 v_{\mathrm{A}}\langle\rho\rangle}$$

Improved drift model accounting for internal and external (Pegourie) connection currents

$$n_0 m_0 \frac{dV_d}{dt} = \frac{1}{1+\left(1-P_{Alf}-P_{con}\right)\left(L'_{con} n_\infty m_\infty / Z_0 n_0 m_0\right)} \times$$

$$\left[\frac{2\left[\left(p_0^e+p_0^i\right)\left(1+M^2/2\right)-\left(p_\infty^e+p_\infty^i\right)\right]}{R}\frac{qR}{Z_0}\sin\left(\frac{Z_0}{qR}\right) - \frac{V_d B_\infty^2}{Z_0}\times\left\{P_{Alf}\frac{2H\left(f_0^i-f_c^i\right)}{\mu_0 C_A} + P_{con}\frac{\left[1-e^{-t/(\tau_{coll}^e+\tau_L)}\right]\pi R_0^2\sigma_\infty}{L_{con}}\right\}\right]$$

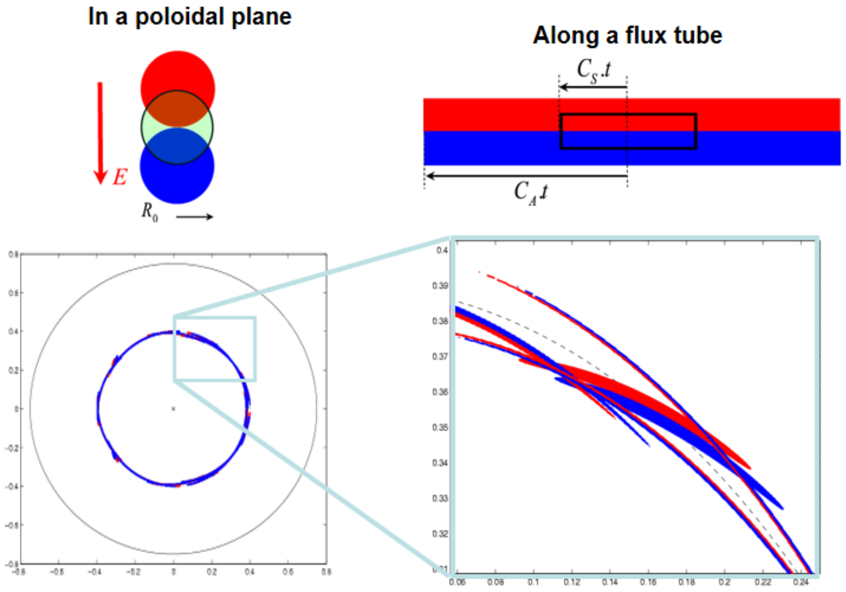
Violet term: grad-B grift

Blue term: positively and negatively charged parts of the cloud are connected, and parallel (Pegourie) current can flow.

Red term: Alfven wave drag (no self connection)

Green term: positively and negatively charged parts of the cloud are connected by the same polarity – no currents

Brown term: internal connection currents



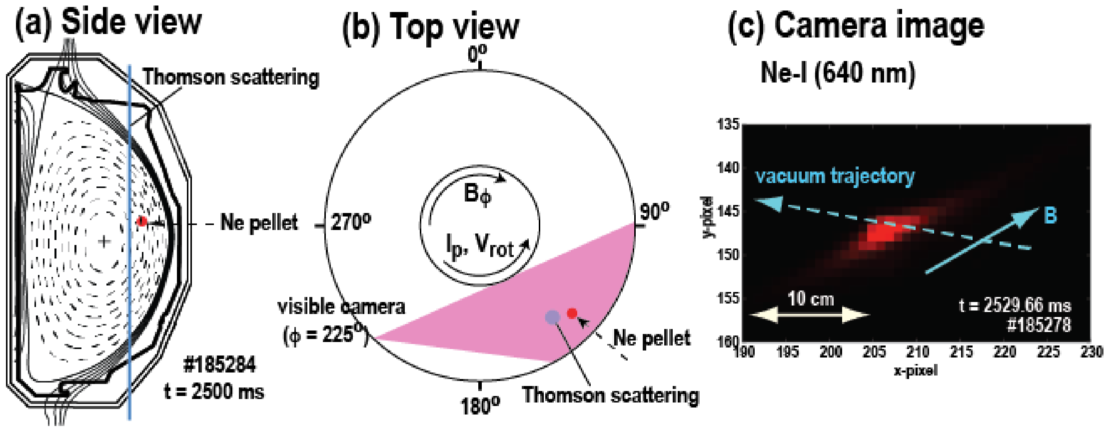
After $C_A t$ = 7 toroidal turns in each direction (few 10 × μs)

P_{con} (P_{Alf}): Proportion of cloud self-connected (+ vs. -) (NOT self-connected) at time t

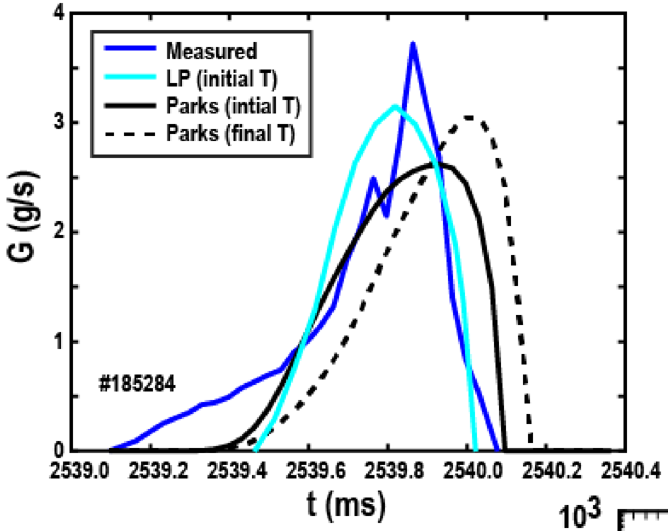
L_{con} : Harmonic average of the length of the field lines self-connecting the plasmoid [m]

Validation of Lagrangian Particle Pellet code

- LP code agrees with experiments on ablation rates of deuterium fueling pellets in various tokamaks. In particular, LP reproduces the experimentally measured ablation rate of 39 g/s for canonical conditions (Te = 2 keV, ne = 1.e14 1/cc, r_p = 2mm, B = 1.6T)
- Computed plasmoid drift velocities agree with experimental measurements in ASDEX Upgrade (slide 11)
- Lagrangian particle (LP) code was used for simulations of small (~1.3mm diameter) neon pellets into DIII-D Super-H plasma. Simulations are in good agreement with DIII-D experimental data. [E. M. Hollmann, N. Naitlho, S. Yuan, R. Samulyak, P. Parks, D. Shiraki, J. Herndal, and C. Marini, Phys. Plasmas 29, 092508 (2022); doi: 10.1063/5.0106724.]
- Simulations agree with experiments on both the pellet ablation rate evolution and photon efficiency.

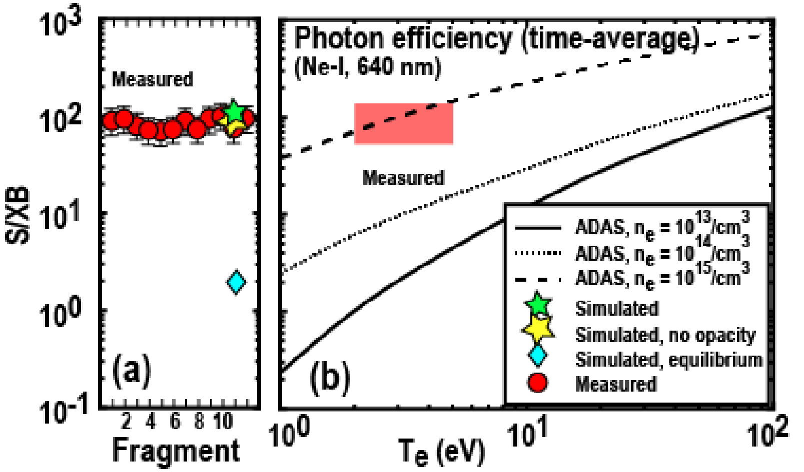


- Small neon pellets (mass = 1.7 Torr-L $\Longrightarrow r_p = 0.65$ mm), one per plasma discharge, were fired inward radially at typical velocities $\approx$ 200 m/s from the outer midplane
- Diagnostics used were a tangentially-viewing fast camera, Fig. (b), to image the neon pellet ablation plume, Fig. (c), and a vertical Thomson scattering (TS) system to measure background plasma $T_{e\infty}$ and $n_{e\infty}$ profiles.
- In Fig. (c), the pellet emission tends to be elongated along the magnetic field direction B, as expected from simulations.

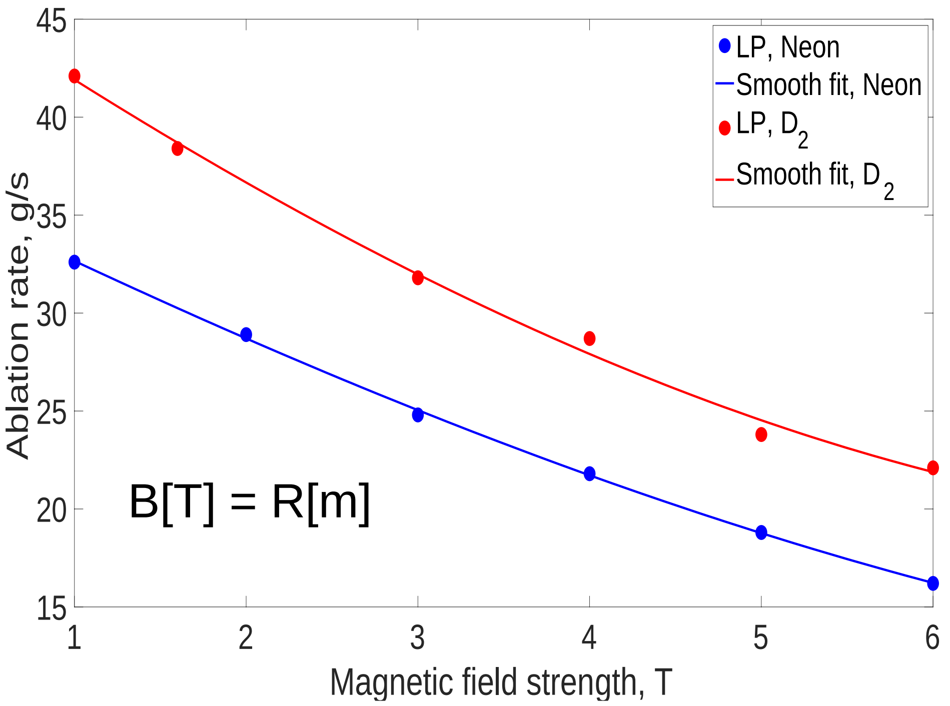


Measured and simulated pellet ablation rate evolution. LP code does not contain any adjustable parameters. LP simulations are self-consistent and give good agreement with the experiment.

Trajectory-averaged photon efficiency S/XB for Ne-I 640 nm obtained from experiment (red circles) and LP + PrismSPECT simulations (other points).



Ablation rates for Neon and Deuterium pellets in magnetic fields



- With grad-B drift, we observe weaker reduction of the ablation rate in magnetic field compared to simulations with fixed shielding length (FronTier code, NF2007, NF2021)
- The shielding length decreases with the increase of the magnetic field
- Without the grad-B drift, the ablated material is completely confined to a narrow ablation channel by the Lorentz force. With the increase of the magnetic field, the ablation channel narrows, increasing the density in the channel, the pellet shielding, and reducing the ablation rate. Such a confinement does not take place in the presence of grad-B drift : the ablated material drifts across magnetic field lines and makes the shielding effect less sensitive to the magnetic field changes.

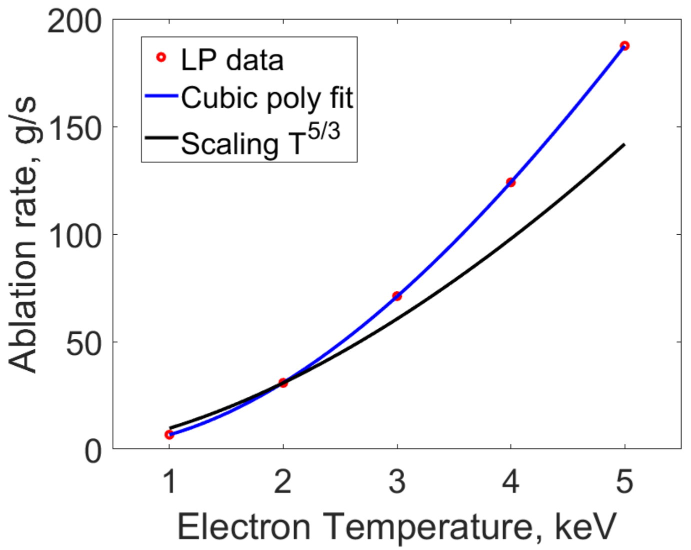
B (T) Neon	Shielding length, cm	G(LP, g/s)
1	21	26.2
2	17	24
4	15	21
5	13.5	19.5
6	12.5	18.2

The scaling of pellet ablation rates deviate from the theoretical scaling law

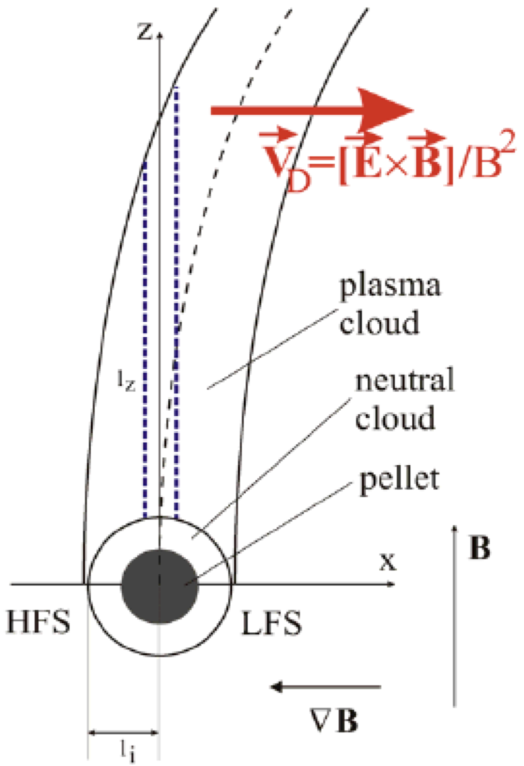
$$G \sim T_{e\infty}^{\frac{5}{3}} n_{e\infty}^{\frac{1}{3}} r_p^{\frac{4}{3}}$$

in the presence of strong grad-B drift flow.

Right plot: Dependence of ablation rate on background plasma Te for 2 mm radius pellet in plasma with ne=1.e14 1/cc and R[m] = B[Tesla] = 4.



Pellet rocket effect: introduction



- The rocket effect is driven by the difference in the cloud pressure on the LFS and HFS of a pellet

$$a = \frac{(p_{\mathrm{HFS}} - p_{\mathrm{LFS}}) \cdot r_p^2 \pi}{m_p}$$

- The Neutral Gas Shielding model contains an empirical adjustable parameter to describe the imbalance of pressure

- A model based on the perturbation theory [I. Senichenkov et al., in: Proceedings of 34th EPS Conference on Plasma Phys., Warsaw, 2007, Paper No. P-4.094, 2007] describes the rocket acceleration based on the background plasma state

- Senichenkov's model underpredicts the ablation rate and overpredicts the rocket acceleration [ASDEX Upgrade data, T. Szepesi et al. Journal of Nuclear Materials 390 - 391 (2009) 507–510]

- Since the rocket acceleration in Senichenkov's model is proportional to the ablation rate, adjusting (increasing) the ablation rate would lead to a greater overprediction of the rocket effect

Lagrangian particle model for pellet rocket acceleration

In the LP code, the difference of the HFS and LFS pressure comes from **three sources.** Smaller shielding length of the cloud at HFS compared to LFS results in following:

1. Decrease of n_e due to charging of the cloud and electrostatic shielding (albedo effect) ($n_e \to n_{eff}$) is weaker at the HFS as it is defined at every field line [P.B. Parks, T. Lu, R. Samulyak, PoP 16 (2009) 060705]:

$$n_{eff} = \left(1 - \frac{A}{100}\right) e^{-\Phi_s}, \quad \text{where } A = 23.92 \ln(1 + 0.2014(1 + Z_*)).$$

The sheath potential Φ_s is a solution of the following nonlinear equation

$$\exp(-\Phi_s) - \sqrt{\pi\Phi_s}\,\mathrm{erfc}(\sqrt{\pi\Phi_s}) = \frac{\alpha}{1-\mu_s},$$

where the attenuation μ_s coefficient is a function of the normalized cloud opacity u

$$\mu_s(u) = \left[1 + (u/2)^{1/2} - u/4 + 0.5(u/2)^{3/2}\right] \exp(-\sqrt{u/2}) - (u^2/8)E_1(\sqrt{u/2}),$$

$$u = \int_{-\infty}^{\infty} n_e(x,y,z)dz/\tau_{eff}, \quad \tau_{eff} = \frac{1}{0.625 + 0.55\sqrt{1+Z_*}} \frac{T_e^2}{8\pi e^4 \ln\Lambda}.$$

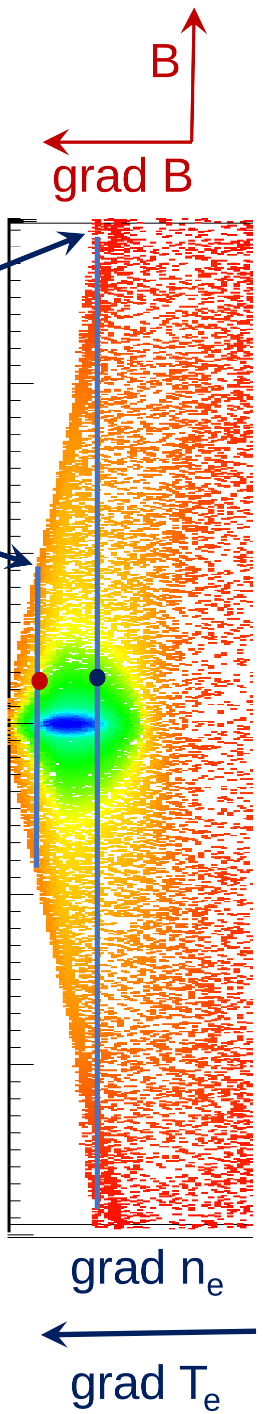
2. Weaker attenuation of hot electrons penetrating cloud at HFS

3. Gradients of n_e and T_e in plasma (in particular in the pedestal)

$n^1_{eff} > n^2_{eff}$

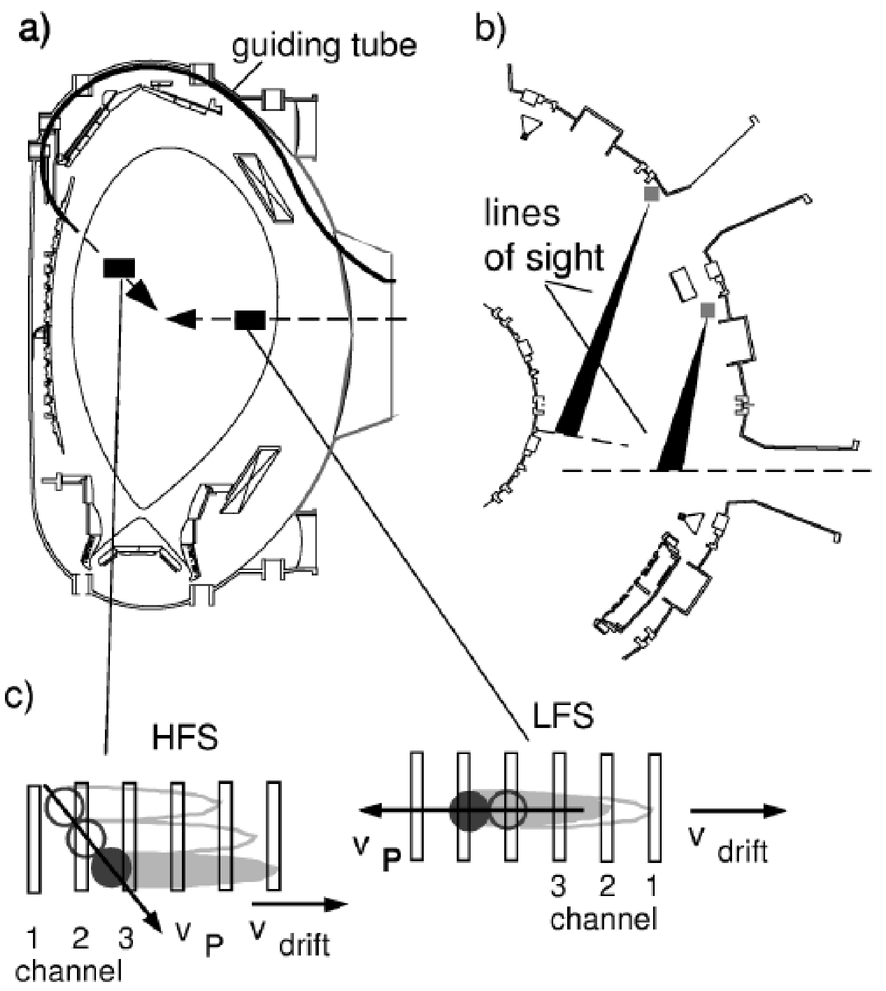
A larger fraction of n^1_{eff} reaches the red point compared to the fraction of n^2_{eff} reaching the blue point.

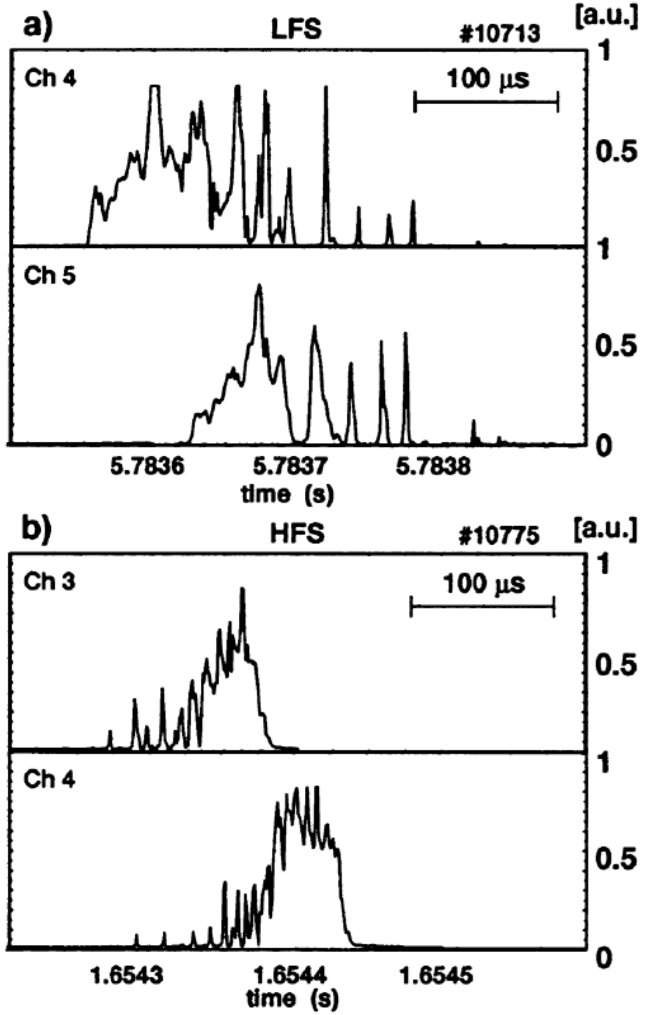
- Sources (1) and (2) increase the acceleration
- (3), gradients of plasma n_e and T_e , may increase or decrease the rocket acceleration



Validation of the pellet rocket acceleration effect in LP simulations: ASDEX Upgrade experiment

H.W. Müller et al 1999, PRL 83, 2199-2202; H.W. Müller et al 2002 Nucl. Fusion 42 301





Schematic of the experiment with observation channels (left) and time signals on selected channels (right).

Tokamak parameters:

- Tokamak radius = 1.65 m
- Plasma radius a = 0.5 m
- Toroidal magnetic field: 2.1 - 1.8 on the axis

Plasma:

- Te = 1.5 - 2.2 keV (in the center)
- ne = 5.4e13 - 9.4e13 1/cc

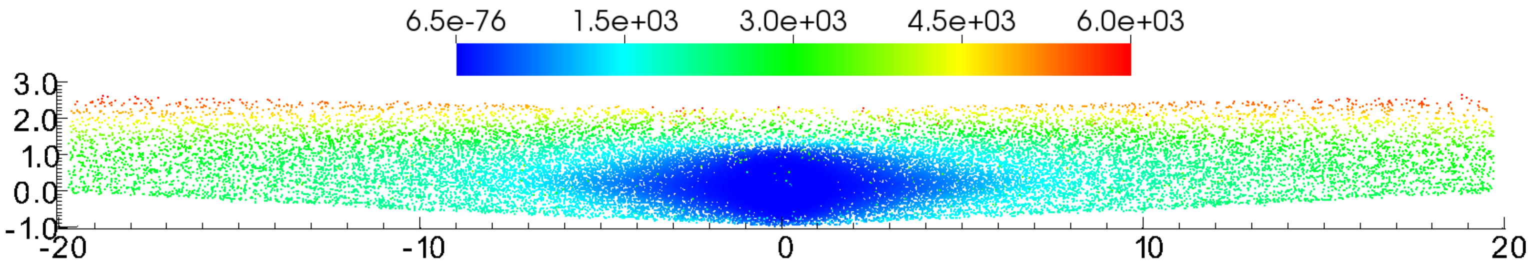
Pellet:

- Deuterium (D2)
- 2.7 - 3.8 e20 atoms
- Radius 1-1.15 mm

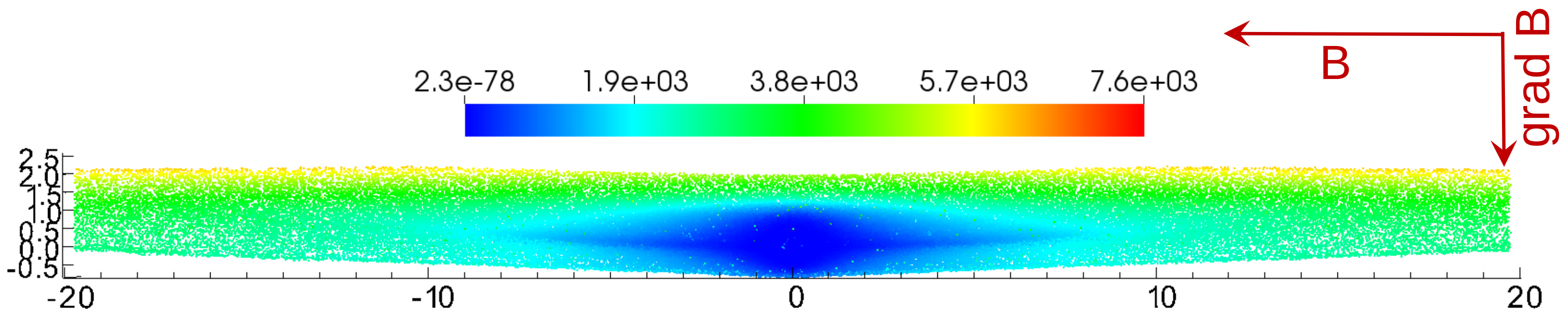
LP simulations of the LFS injection in ASDEX Upgrade

Computed rocket acceleration

- rp = 1 mm, ne = 6.e13 1/cc, Te = 2 keV:
  a = **1.7e5 m/s^2**
- rp=0.5 mm, ne=6.e13 1/cc, Te=2 keV:
  a = **2.4e5 m/s^2**
- rp=0.5 mm, ne=9.4e13 1/cc, Te=2.2 keV:
  a = **7.e5 m/s^2**



Grad-B drift velocity (m/s) for 1 mm pellet in ne=6.e13 1/cc, Te=2 keV plasma



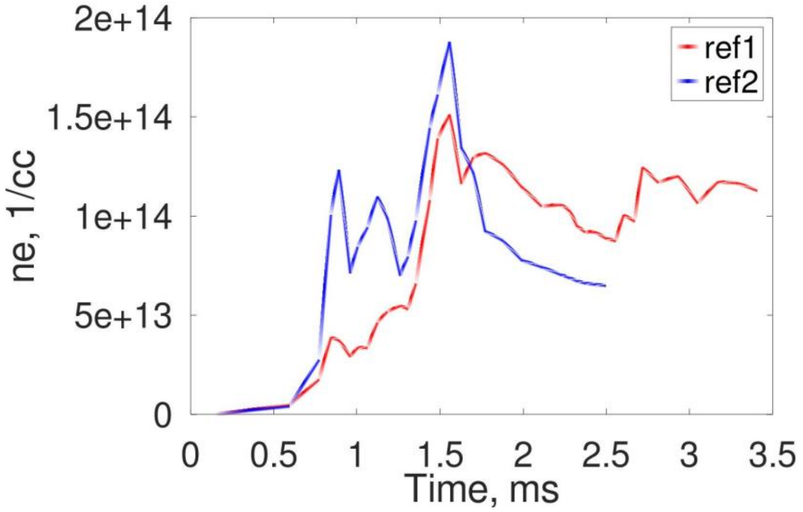
Grad-B drift velocity (m/s) for 0.5 mm pellet in ne=9.4e13 1/cc, Te=2.2 keV plasma

Experiment:

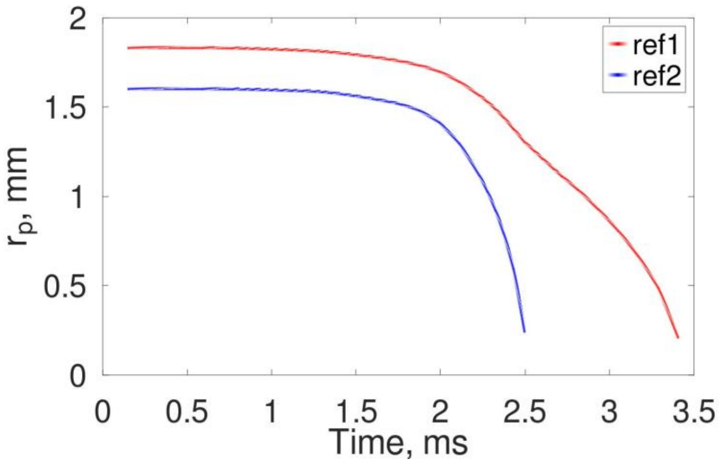
- Average rocket acceleration for LFS injection is 4.e5 m/s^2
- Grad-B drift velocity in the range from 1.e3 to 1.e4 m/s

- Computed average value of the pellet rocket acceleration agrees with experimental measurements
- Computed plasmoid drift velocities are within the range of experimental values
- Additional validations are underway using recently obtained measurements from ASDEX upgrade

Rocket effect validation II: trajectories of vanguard SPI fragments in JET

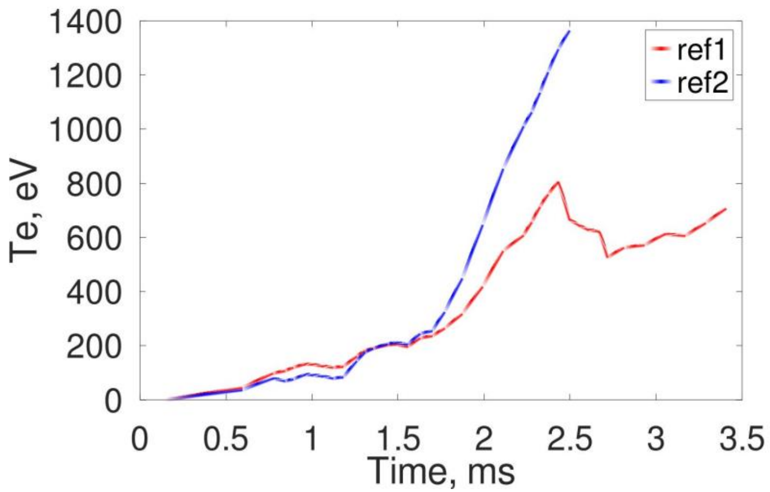


Plasma density at the location of fragments

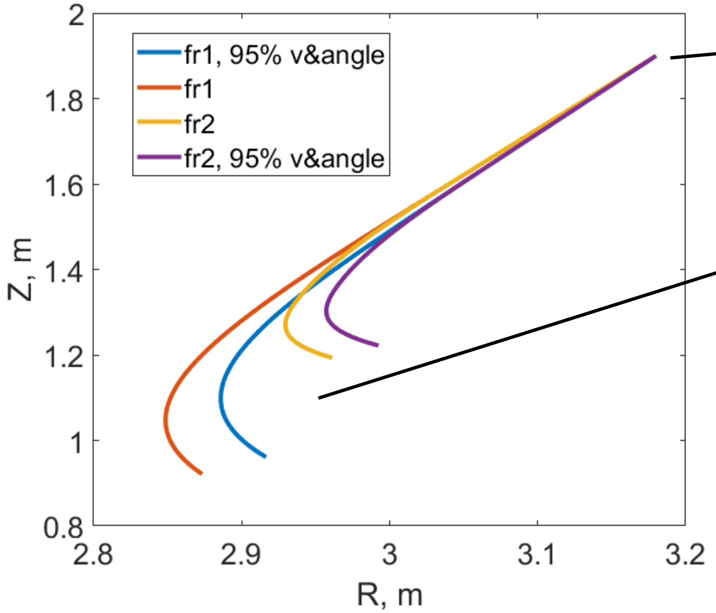


Evolution of fragment radii

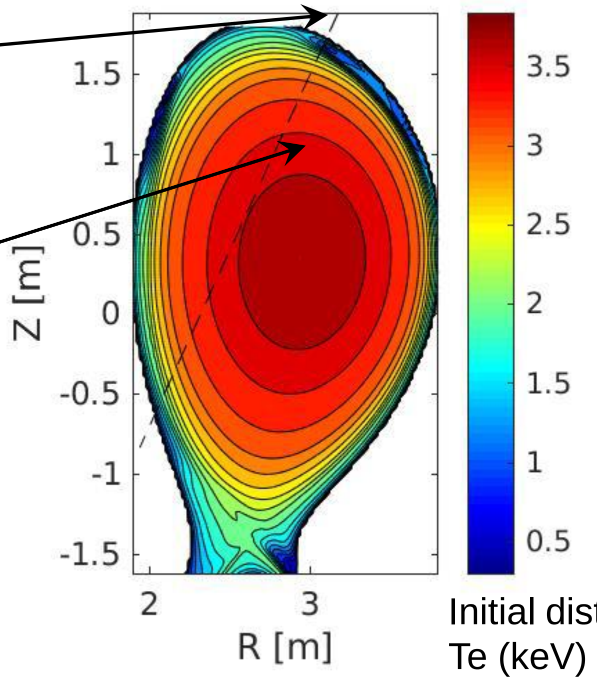
- Strong deviation of initial fragments was observed in JET SPI experiments
- Lagrangian particle simulations used plasma T_e and n_e along estimated trajectories from JOREK simulations (courtesy Mengdi Kong, EPFL).
- Initial fragment velocity = 300 m/s; angle=25^o
- Computed fragment trajectories due ablation and rocket acceleration are in good agreement with JET experimental observation



Plasma temperature at the location of fragments

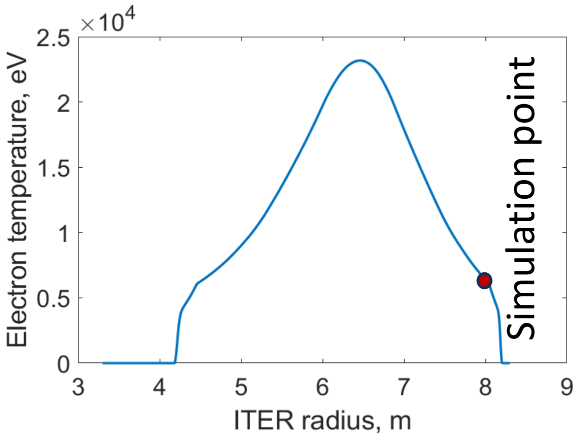


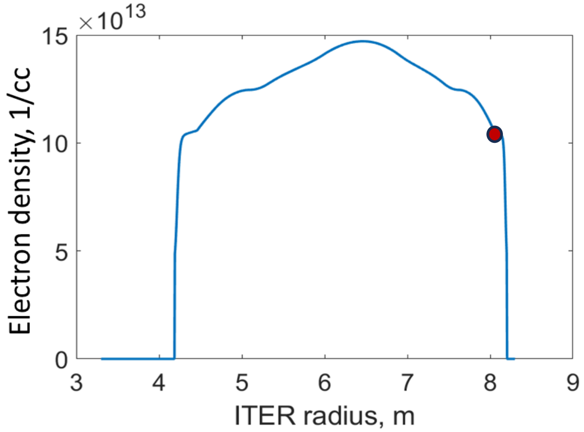
Computed trajectories of fragments

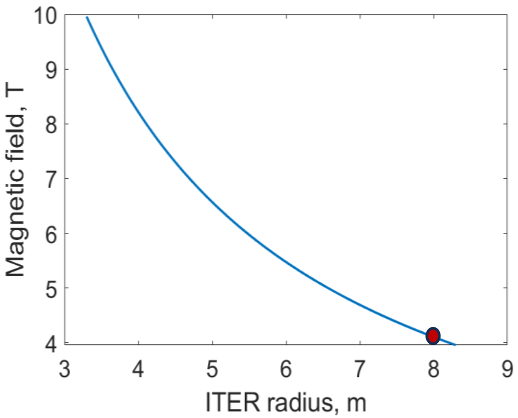


Initial distribution of Te (keV) in JET

Rocket acceleration of H2 fragments injected into ITER from LFS







Plasma state:

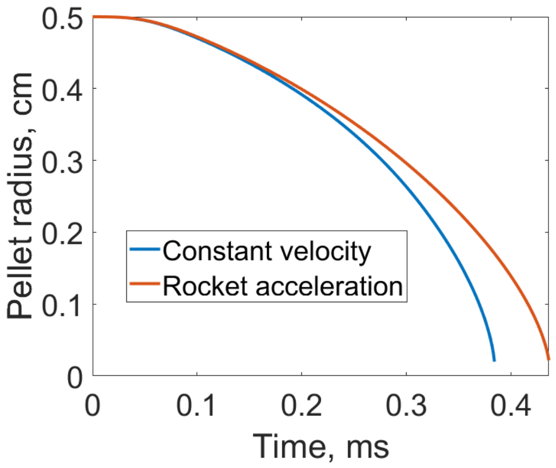
- Radial coord. = 8 m
- Magnetic field = 4T
- ne = 1.e14 1/cc, Te = 5 keV

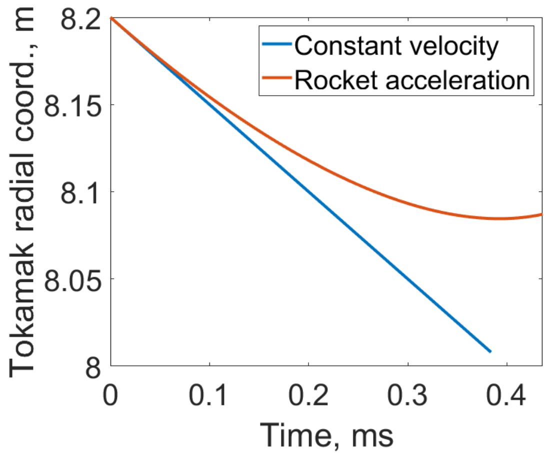
Plasma gradients:

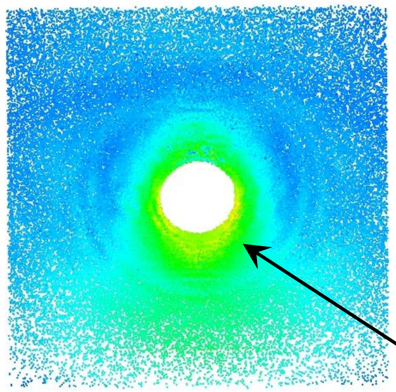
- dn_e/dR = 6.e11 cm^-4
- dT_e/dR ~ 73 - 183 eV/cm (100 eV/cm was used)

Rocket acceleration

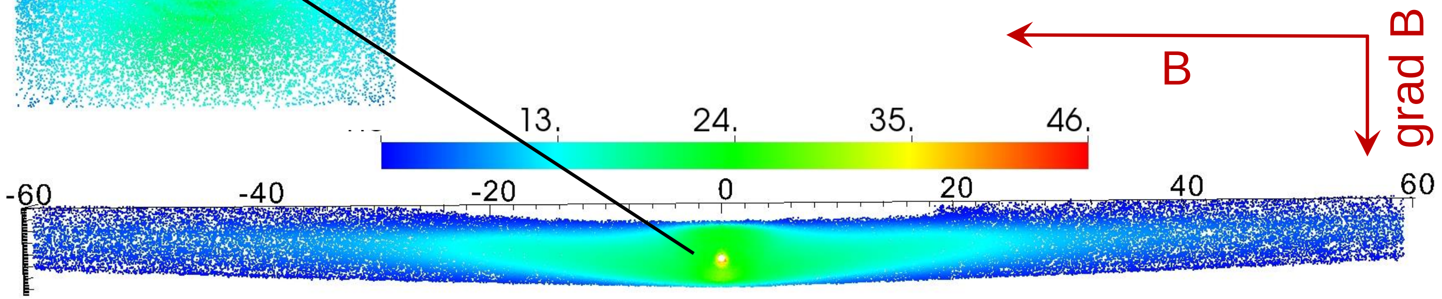
- 5 mm fragment: 1.1e6 m/s^2 (in the pedestal)
- 5 mm fragment: 7.5e5 m/s^2 (in uniform plasma, 32% lower)
- 3 mm fragment: 1.6e6 m/s^2 (in the pedestal)

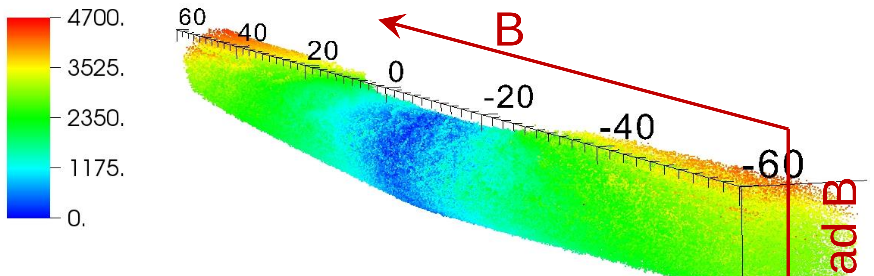






Ablated material pressure, bar, (left and bottom plots) and plasmoid drift velocity, m/s, (right plot) for 5 mm fragment in the pedestal





Computed shielding length = 60 cm

Summary, Conclusions, Future Work

- Grad-B drift strongly influences various aspects of the pellet ablation: the cloud shielding length, ablation rates, improves the efficiency of HFS injection compared to the LFS injection. It creates asymmetry and non-uniform heating of the ablation cloud that leads to the pellet rocket effect.

- Lagrangian particle simulations of pellet ablation rates and plasmoid drifts have been validated

- The hot electron heating module of the Lagrangian particle code has been improved for the simulations of pellet rocket acceleration

- LP's simulations of rocket acceleration has been validated using ASDEX Upgrade experiments. LP simulations reproduced strong rocket effect experienced by first SPI fragments in recent JET experiments.

- Simulations of hydrogen SPI fragments injected into ITER from LFS predict strong (over 1.e6 m/s^2) rocket acceleration. Such a strong acceleration significantly decreases the penetration of vanguard fragments and may cause additional difficulties.

Future work:
- Continue studies of the injection of hydrogen SPI into ITER
- Demonstrate that grad-B drift is among the main factors causing striation instabilities of ablation clouds. Perform direct numerical simulations of striation instabilities.